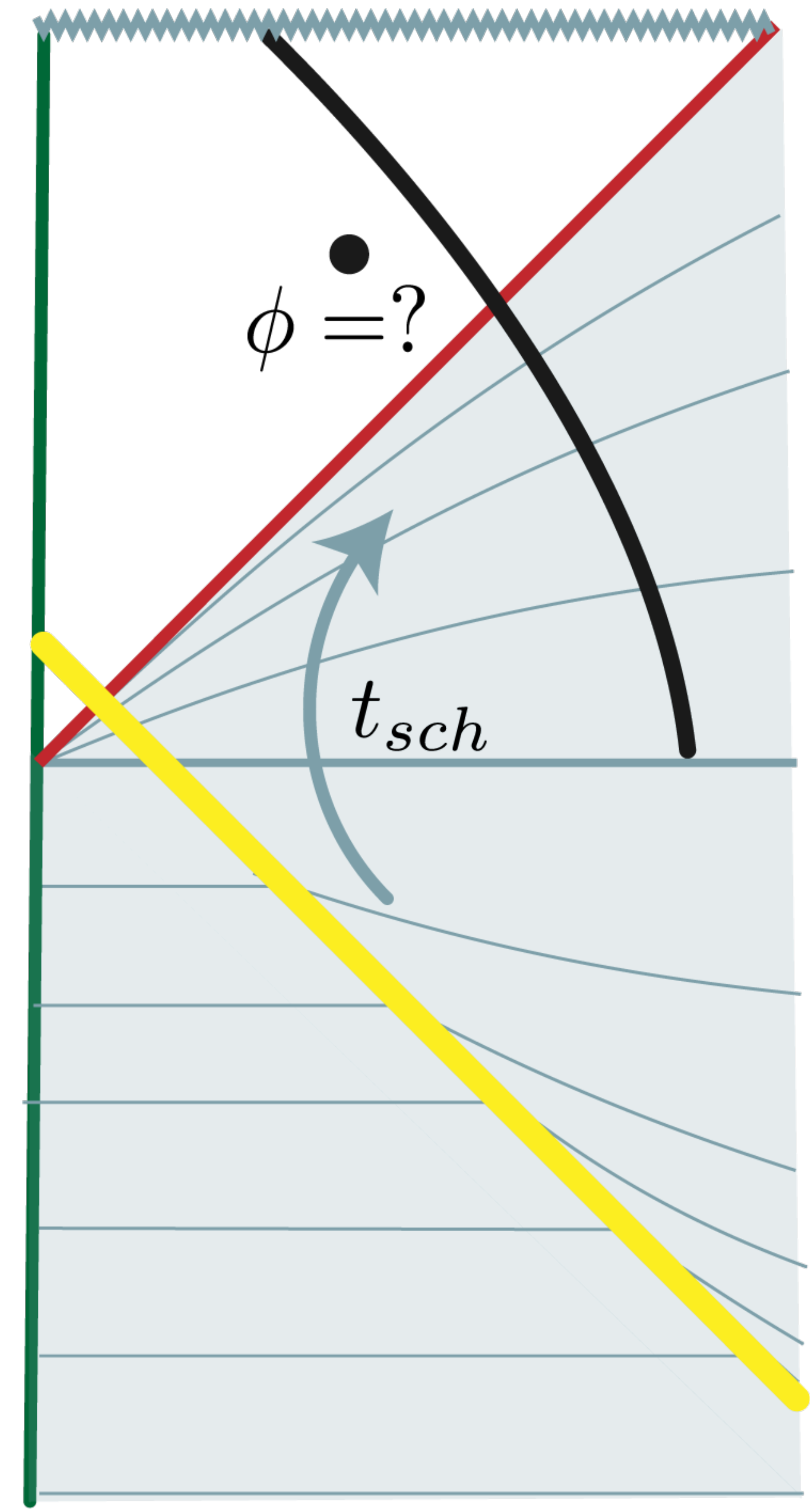
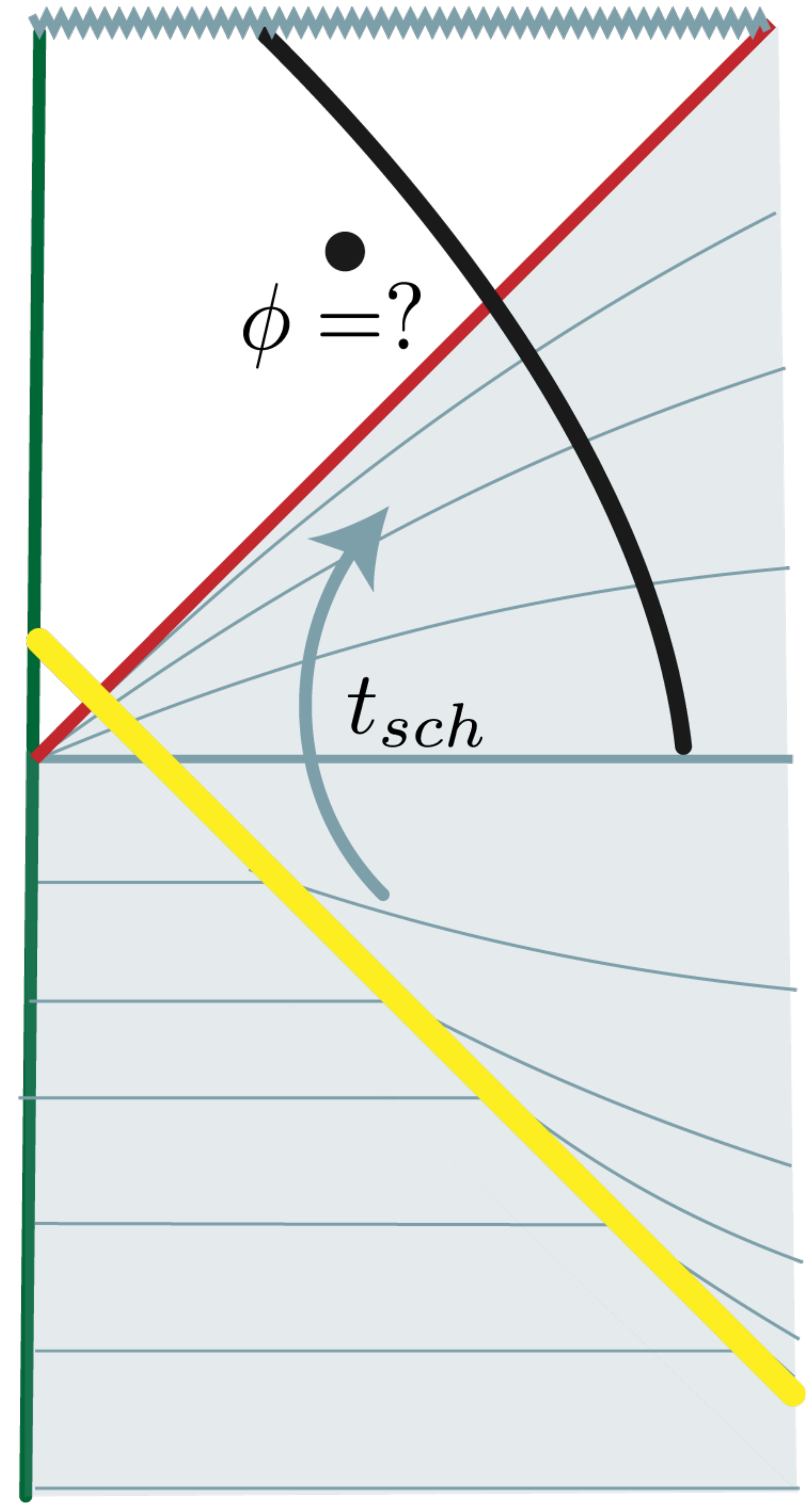
INSIDE HOLOGRAPHIC BLACK HOLES

*Lampros Lamprou w/ Daniel Jafferis, **2009.04476***
*w/ Daniel Jafferis & Jan de Boer, **in preparation***
*w/ Ping Gao, **in progress***

What CFT operator can we measure to learn what an infalling observer sees in the interior of a black hole?

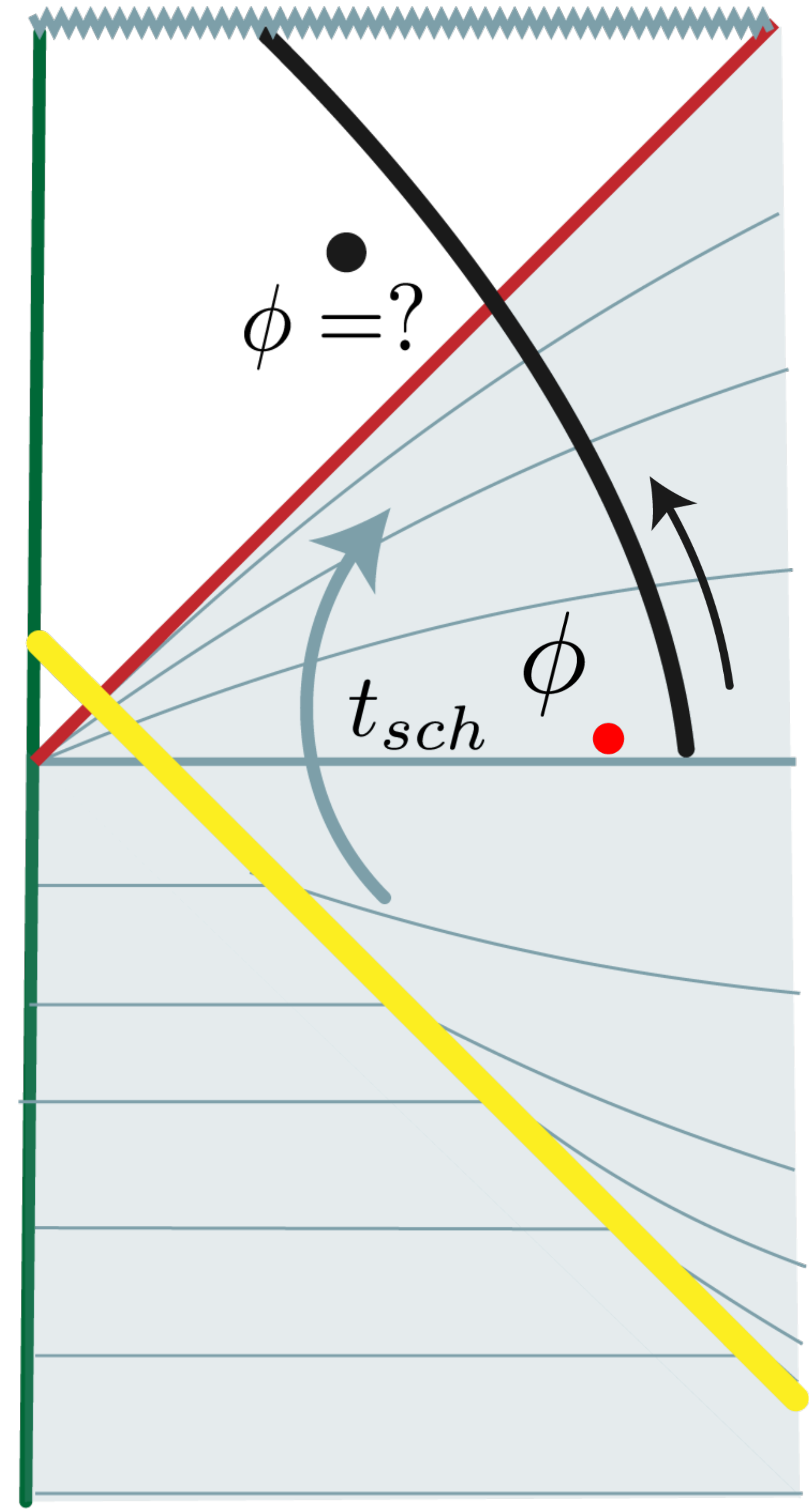


What is the local operator ϕ?



Introduce an observer

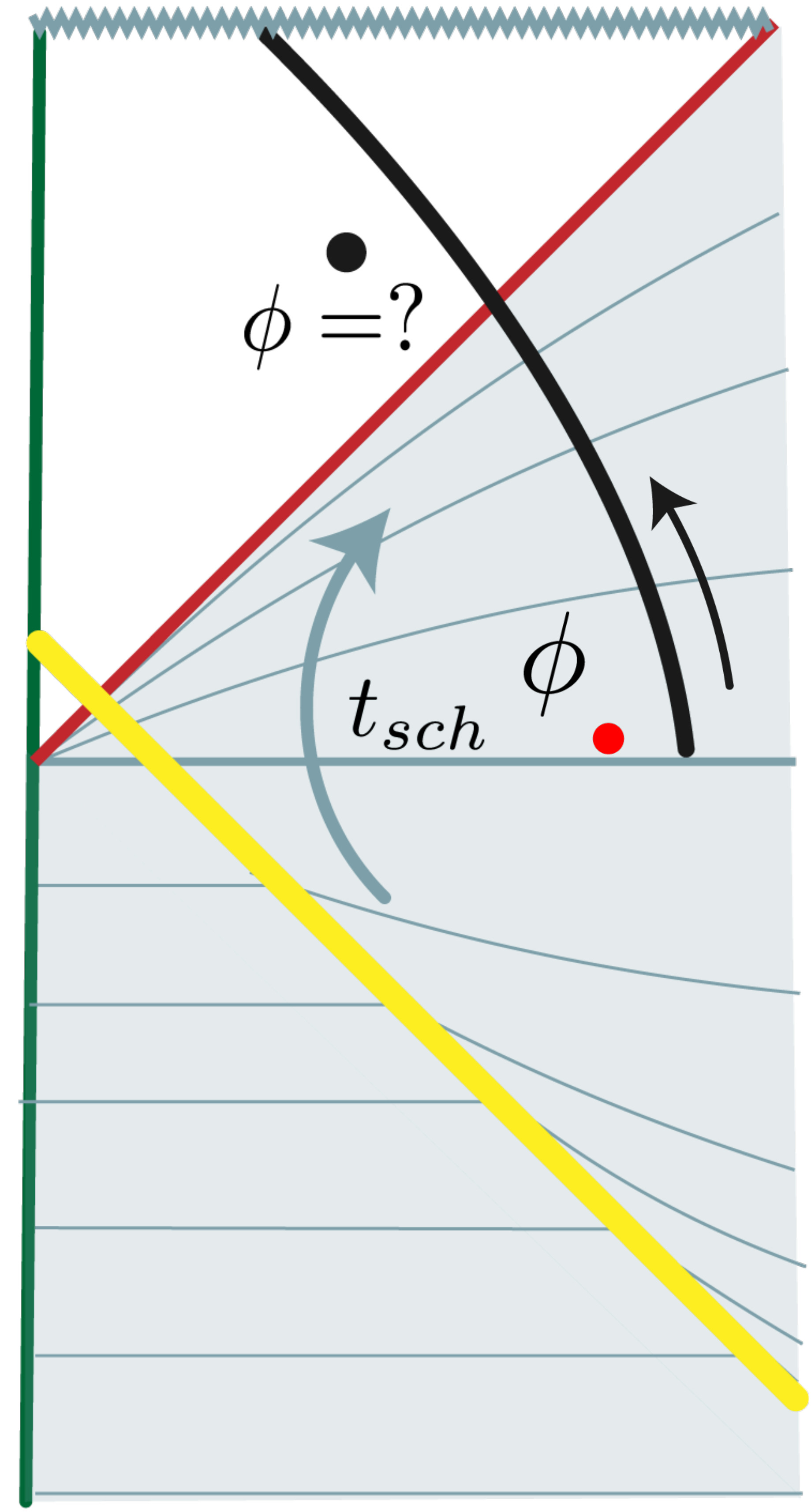
Propagate an exterior operator in proper time

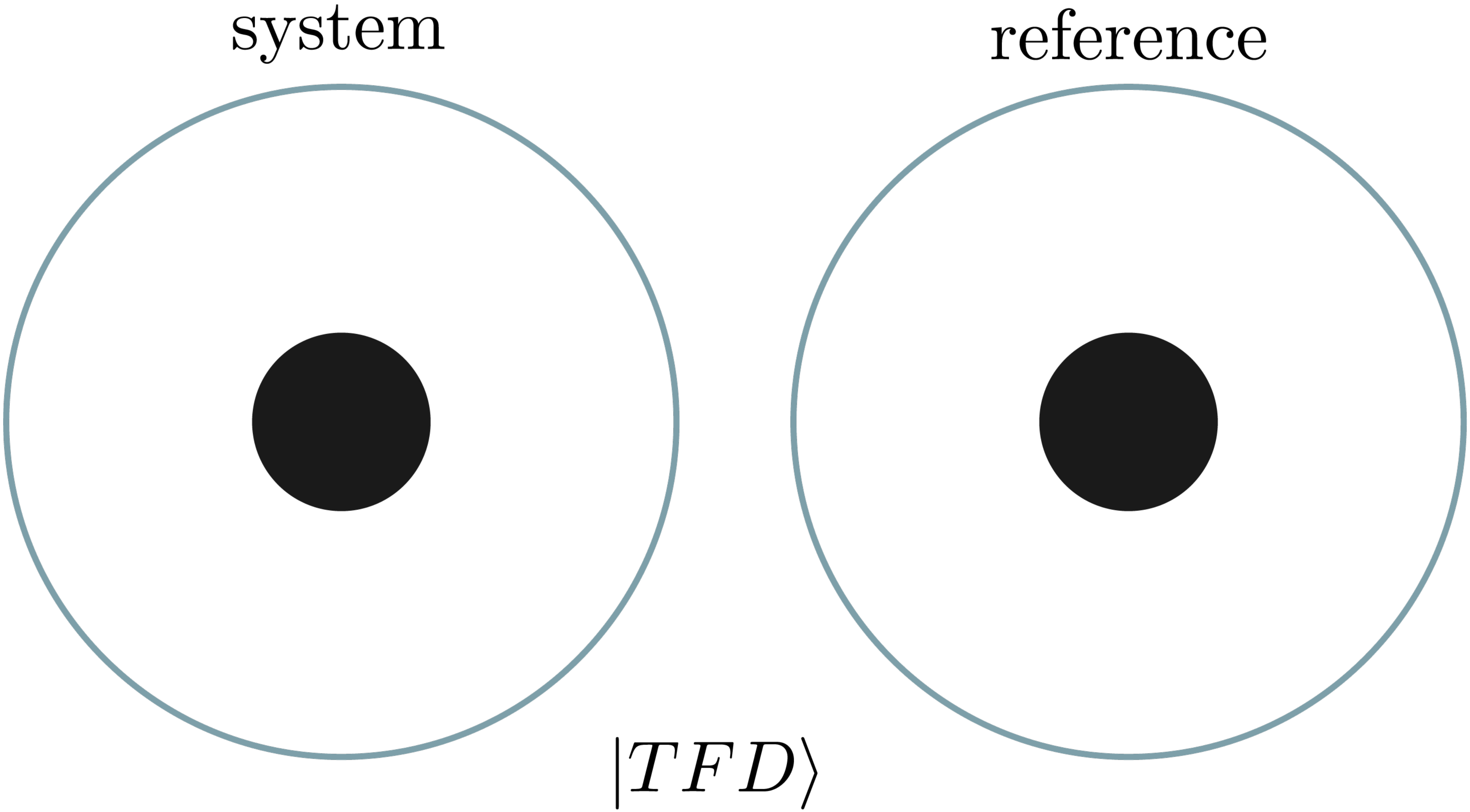


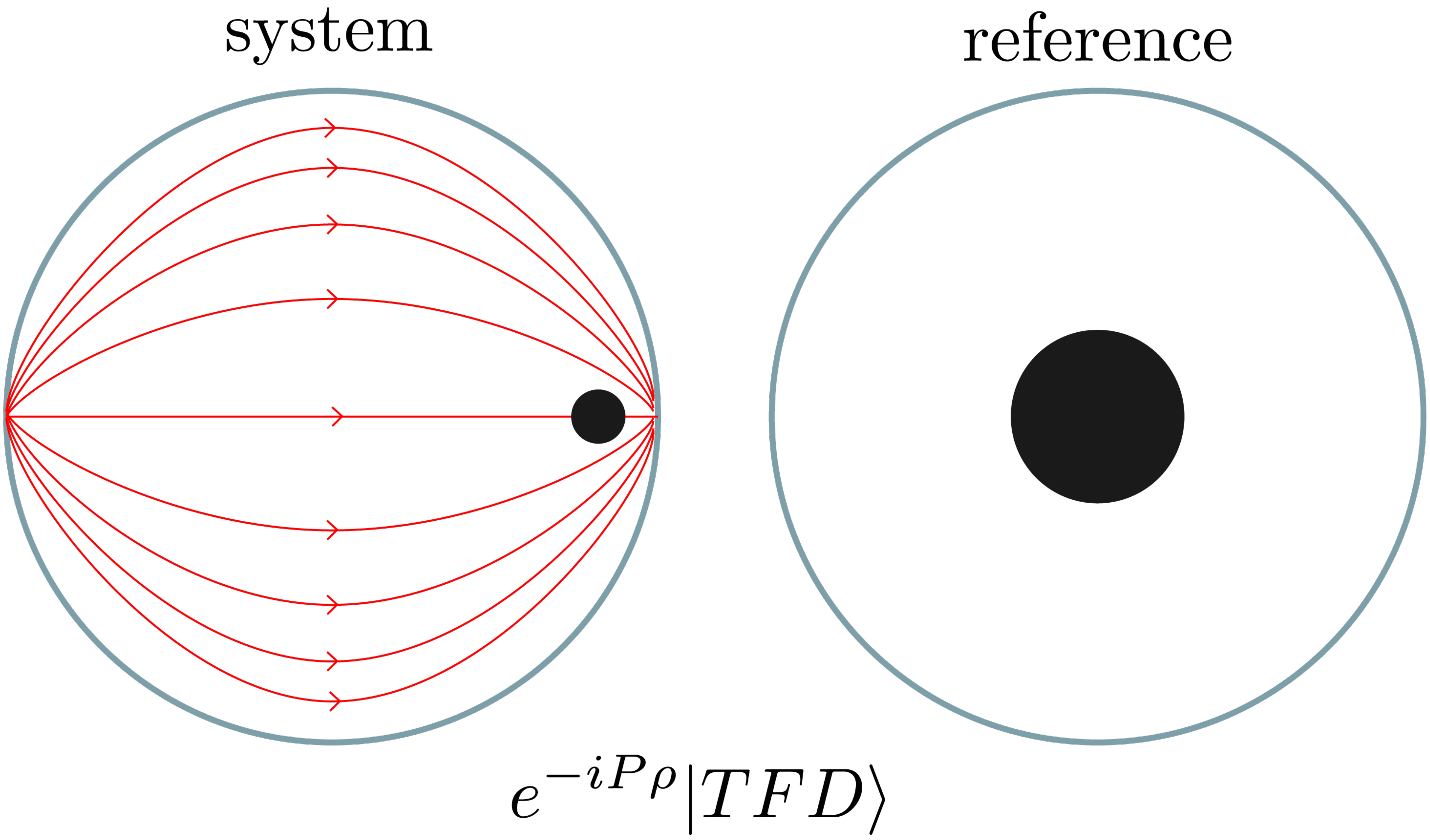
Introduce an observer

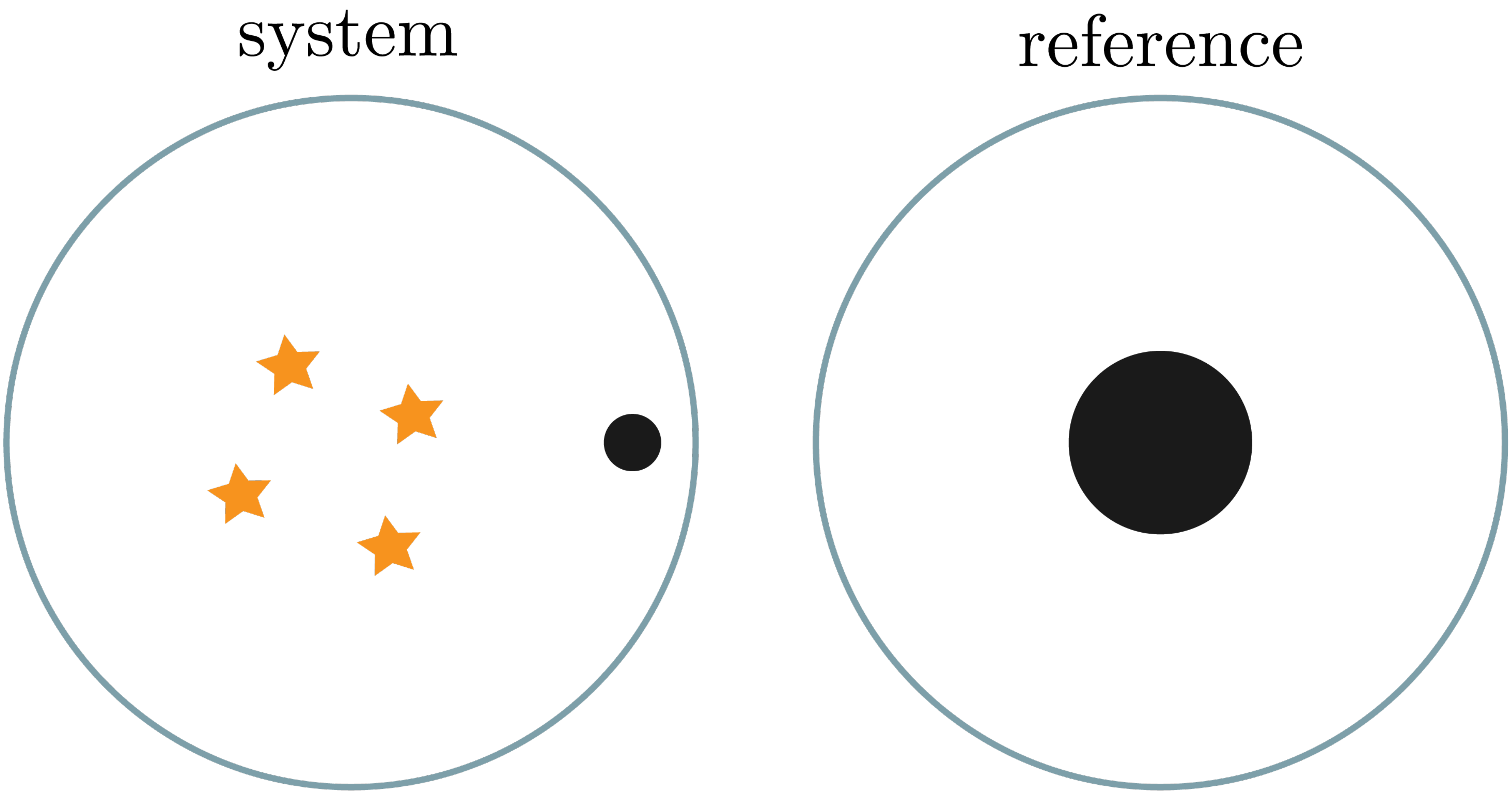
Propagate an exterior operator in proper time

$$H_{pt} = \int_C d\Sigma^\nu \, \xi^\mu T_{\mu\nu} \longrightarrow \text{CFT dual}$$

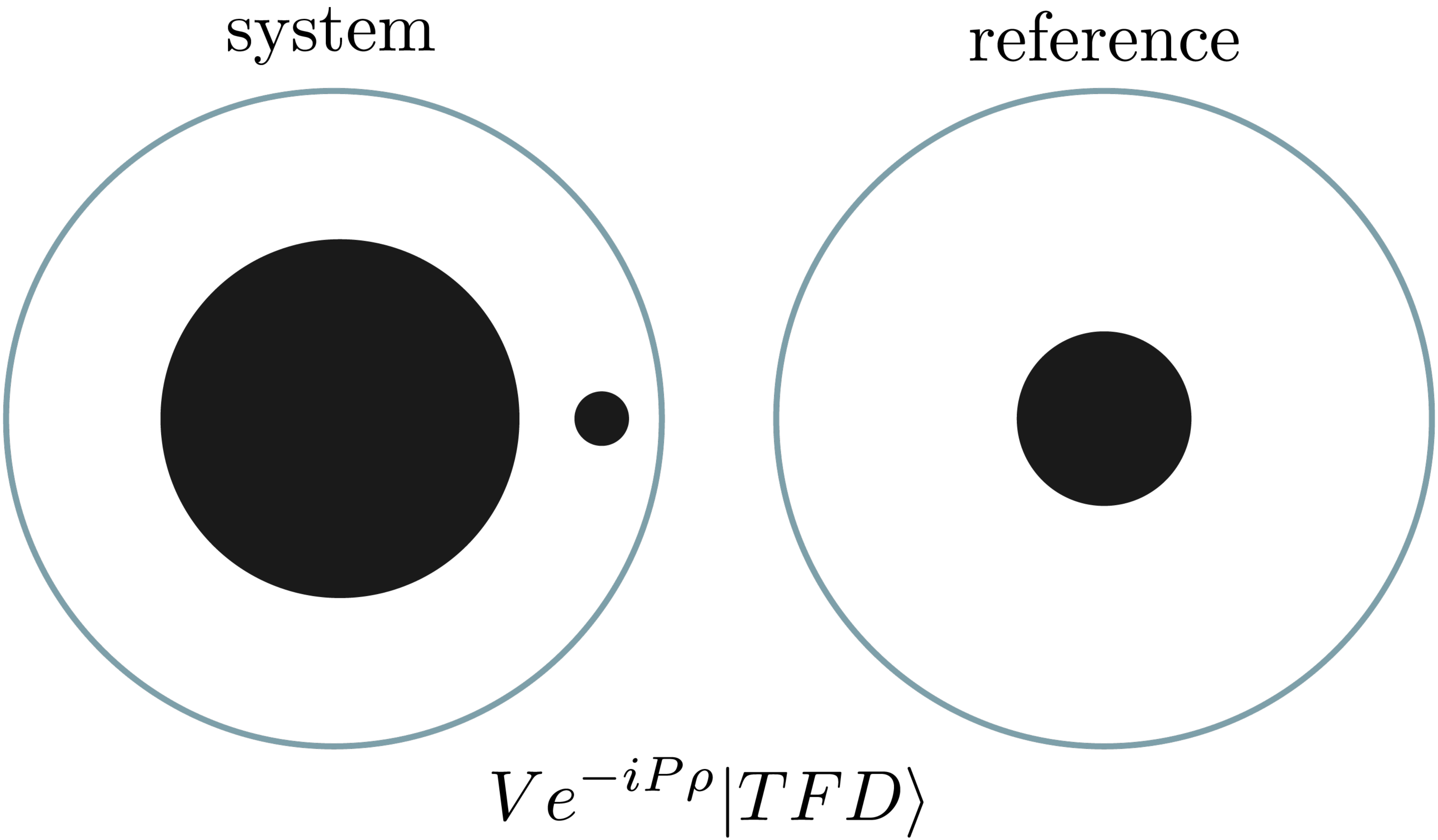



system
reference
$|TFD\rangle$


system
reference
$e^{-iP\rho}|TFD\rangle$



$$Ve^{-iP\rho}|TFD\rangle$$


system
reference
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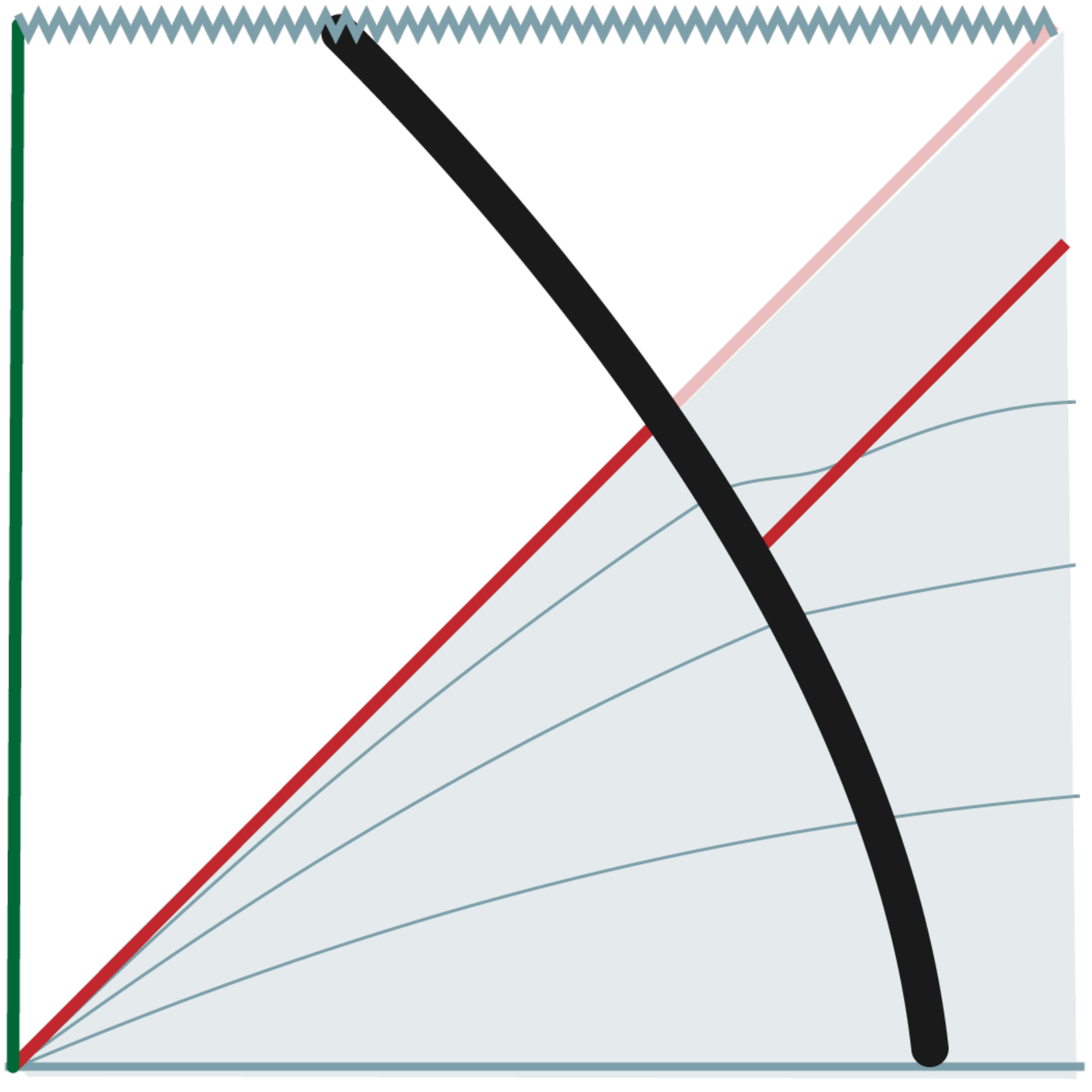
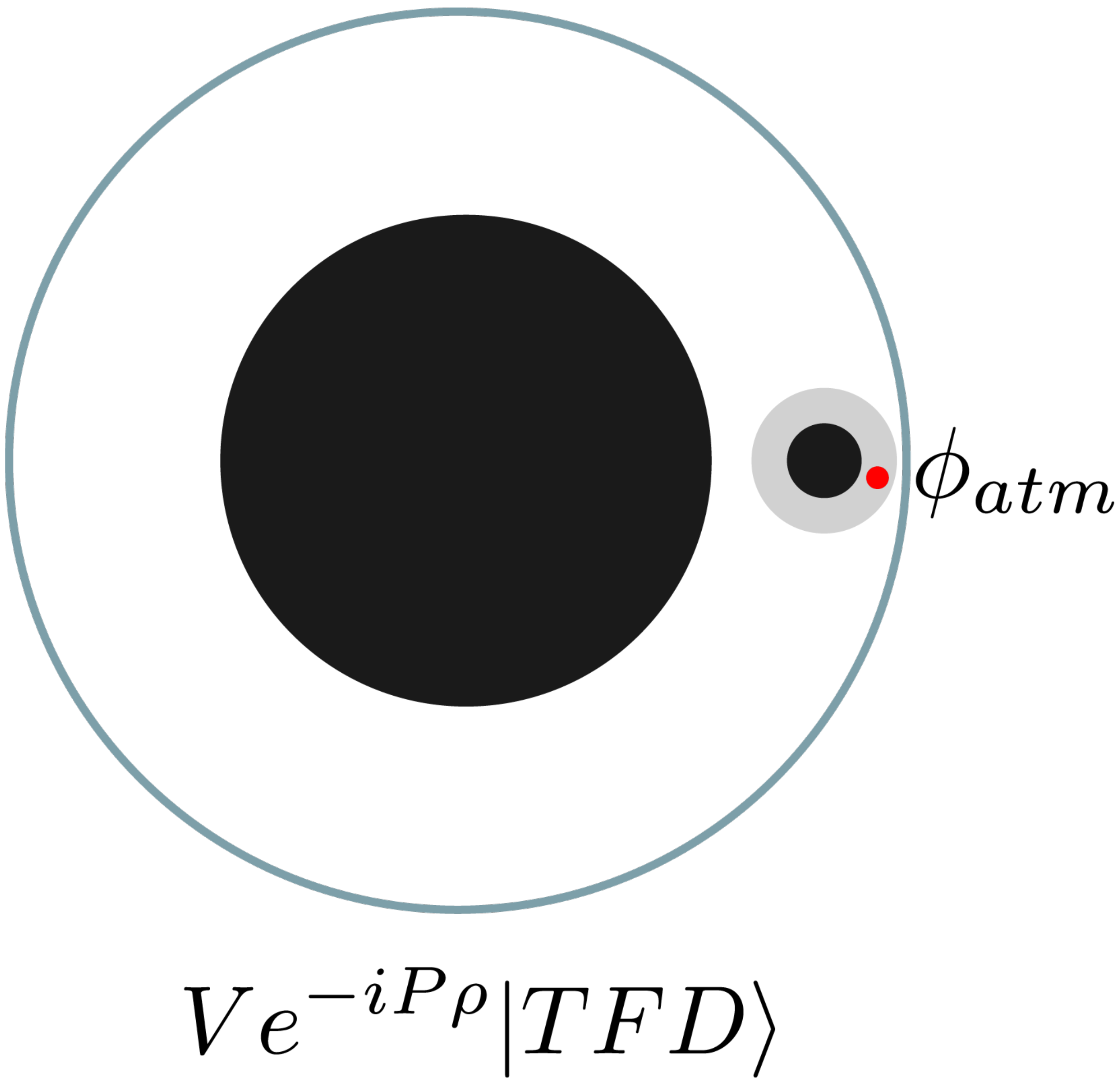
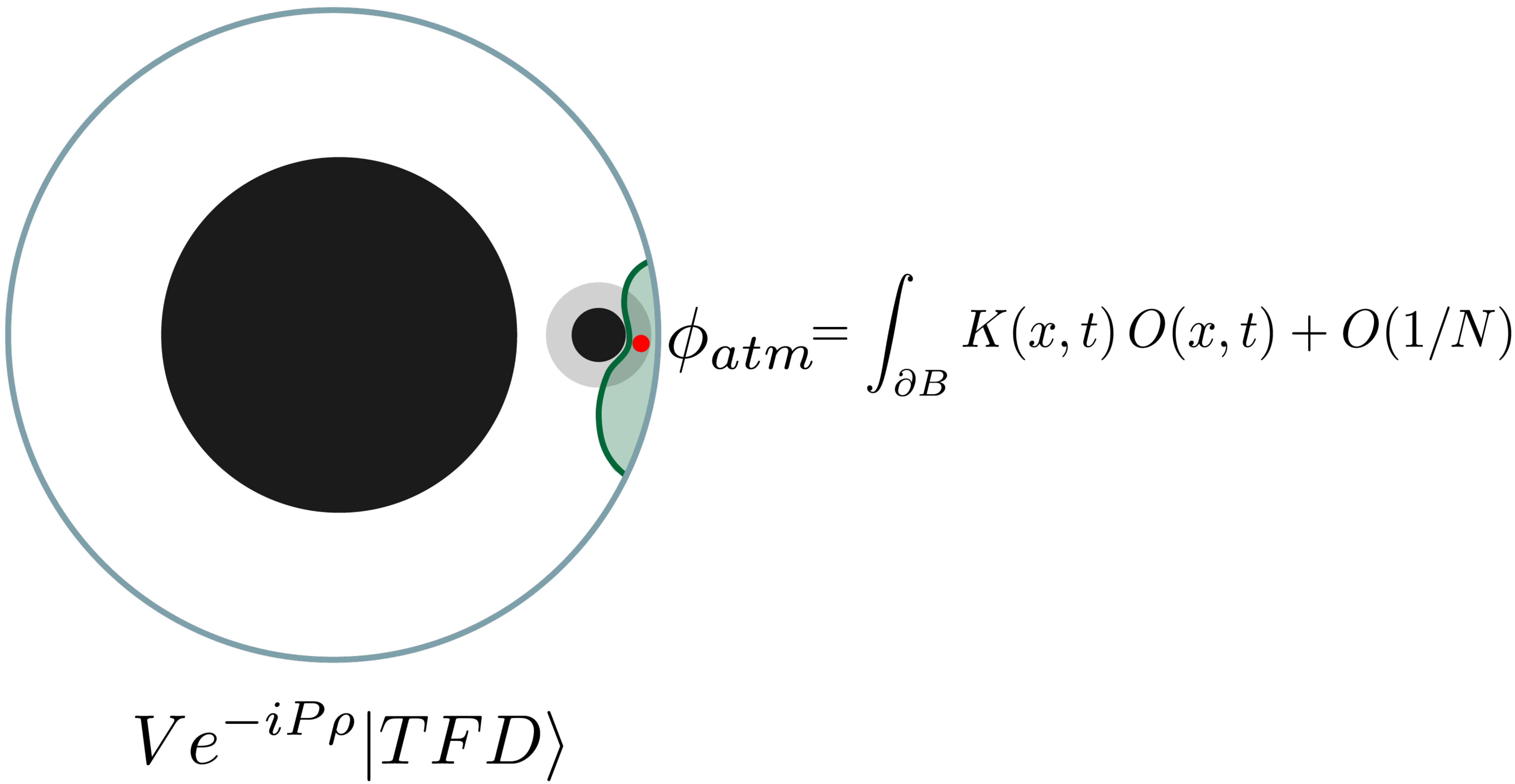
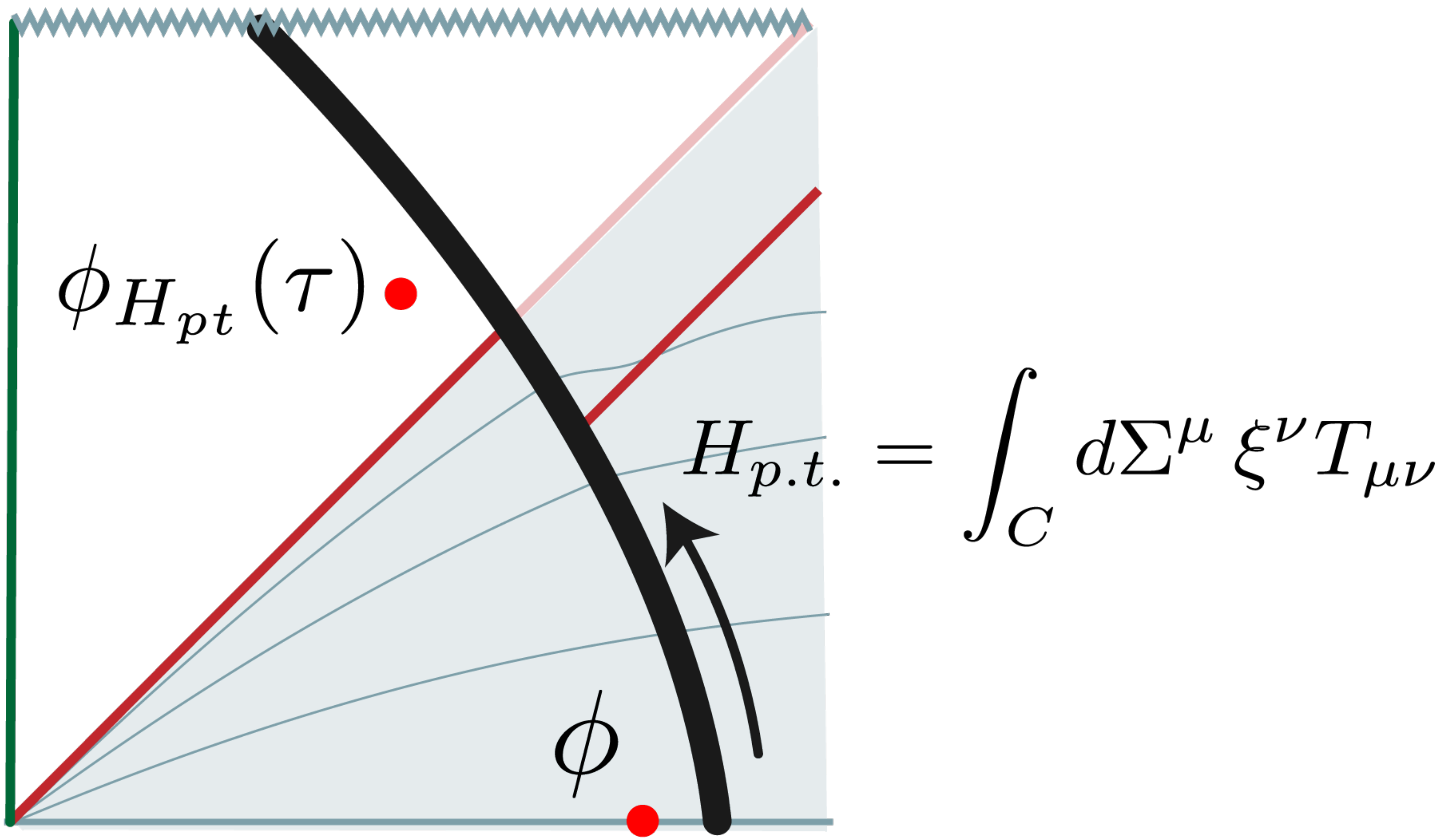


$$e^{-iHt}\,Ve^{-iP\rho}|TFD\rangle$$


ϕ_{atm}
$Ve^{-iP\rho}|TFD\rangle$



$\phi_{atm} = \int_{\partial B} K(x,t)\, O(x,t) + O(1/N)$
$V e^{-iP\rho} |TFD\rangle$



$\phi_{H_{pt}}(\tau)$
$H_{p.t.} = \int_C d\Sigma^\mu \, \xi^\nu T_{\mu\nu}$
ϕ

Euclidean Schwarzschild translations:

$$\langle\psi|\phi_1^\dagger\phi_2(i\beta)|\psi\rangle = \langle\psi|\phi_2\phi_1^\dagger|\psi\rangle$$

when in local thermal equilibrium

Modular Hamiltonian: $K = -\log\left[\mathrm{Tr}_{ref}\left[|\psi\rangle\langle\psi|\right]\right]$

$\Updownarrow$

$$\langle\psi|\phi_1^\dagger e^{-K}\phi_2|\psi\rangle = \langle\psi|\phi_2\phi_1^\dagger|\psi\rangle$$

Near horizon Schwarzschild Hamiltonian H_{pt}

$\Updownarrow$ in local equilibrium

Modular Hamiltonian $K = -\log\left[\mathrm{Tr}_{ref}\left[|\psi\rangle\langle\psi|\right]\right]$

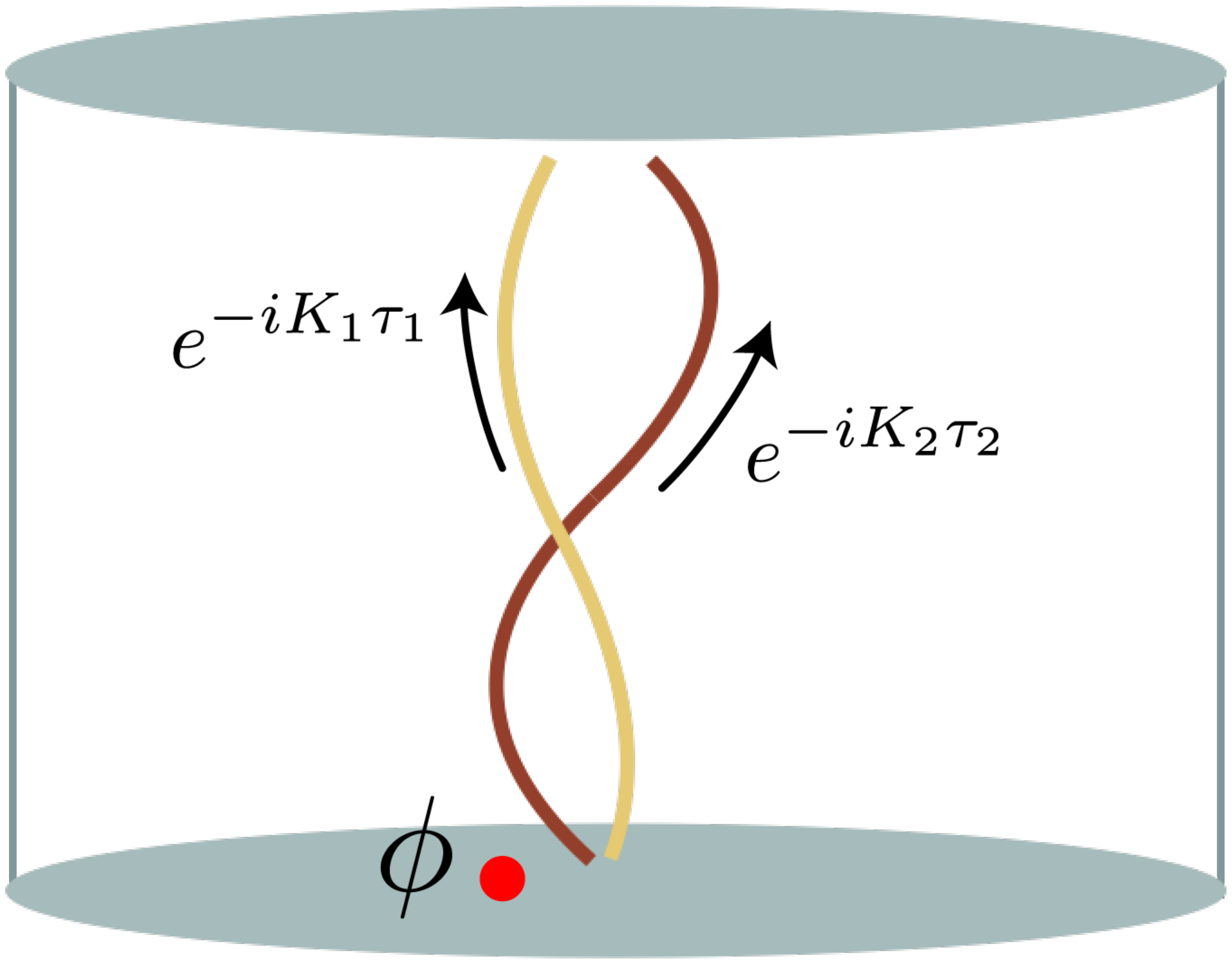
$$|\psi\rangle = Ve^{-iP\rho}|TFD\rangle$$

Question 1: Construction is somewhat abstract. Does it work?

Answer 1: Yes

$\tau_1 - \tau_2 =$ GR time dilation

[arXiv: 2009.04476]



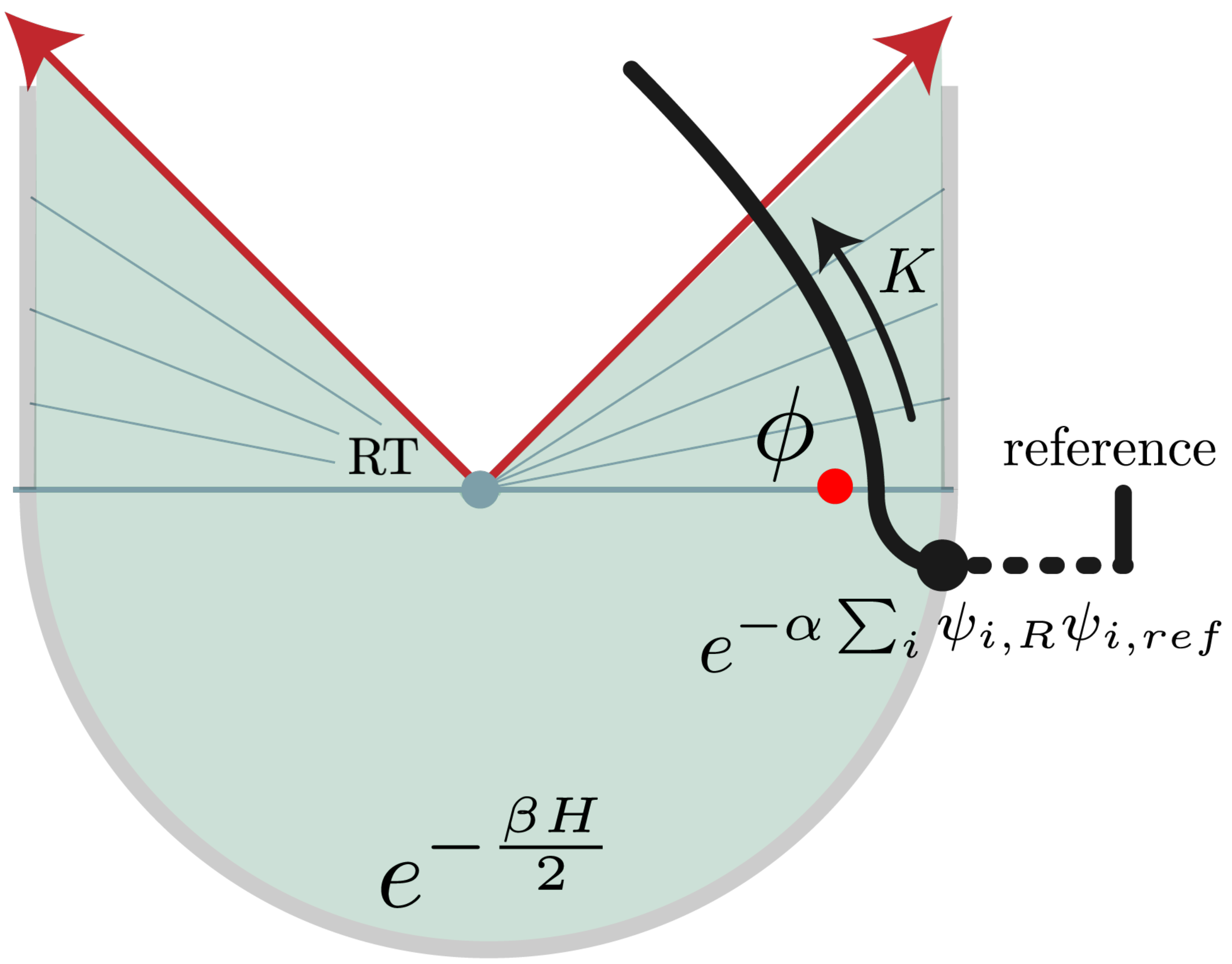
Question 2: Can you actually see behind horizons?

Answer 2: Yes

Explicit construction in SYK

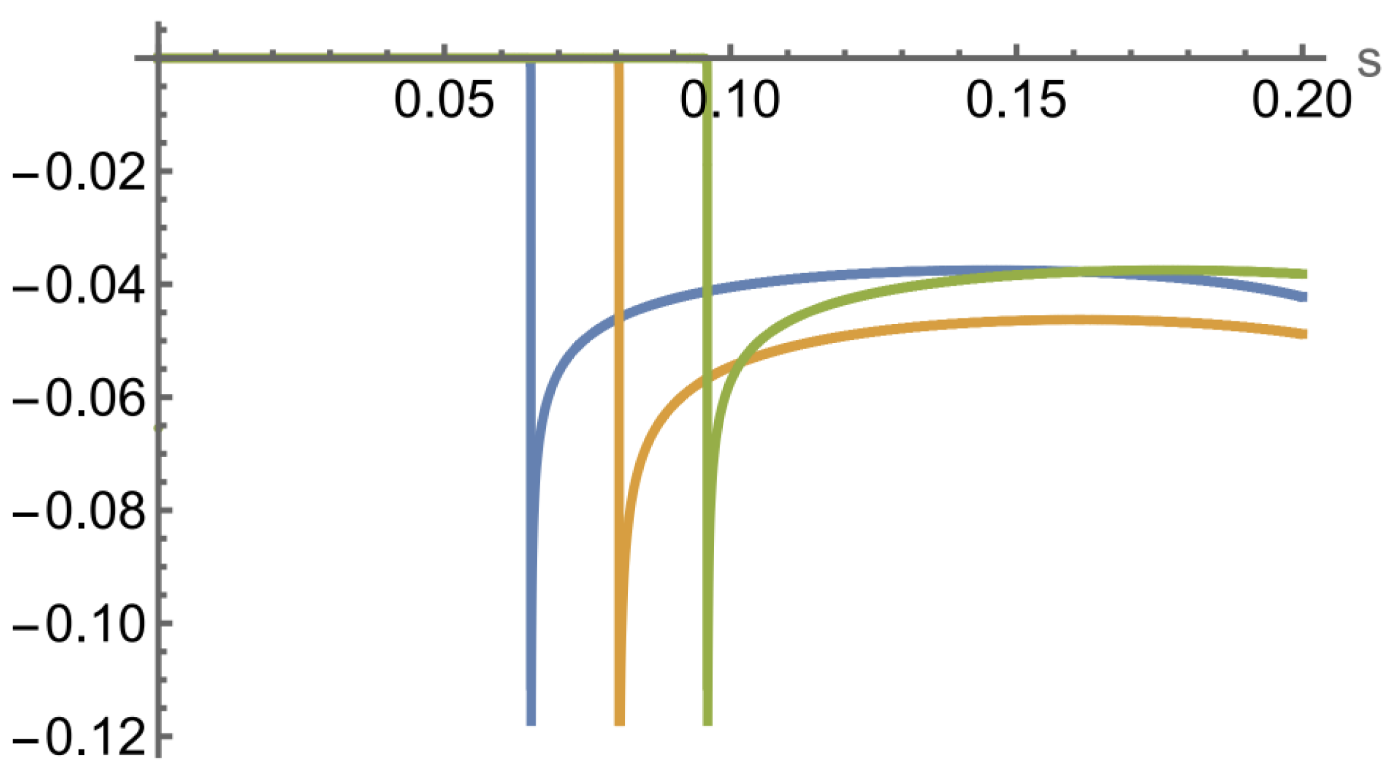
$[\phi_K(\tau), O_L] \neq 0$ for: $\tau \geq \tau_0$

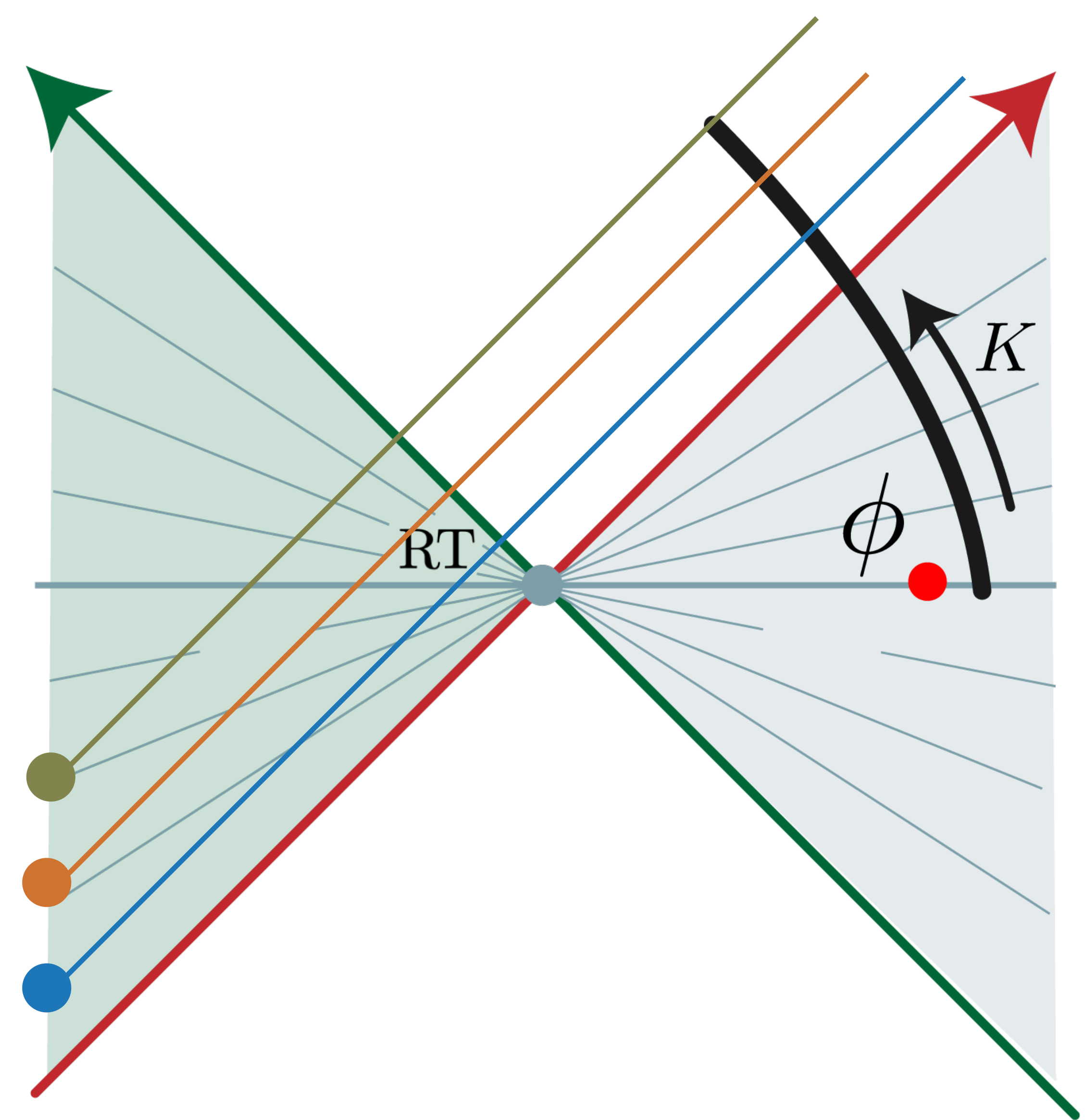
[w/ Ping Gao, in progress]



2-sided AdS_2 wormhole

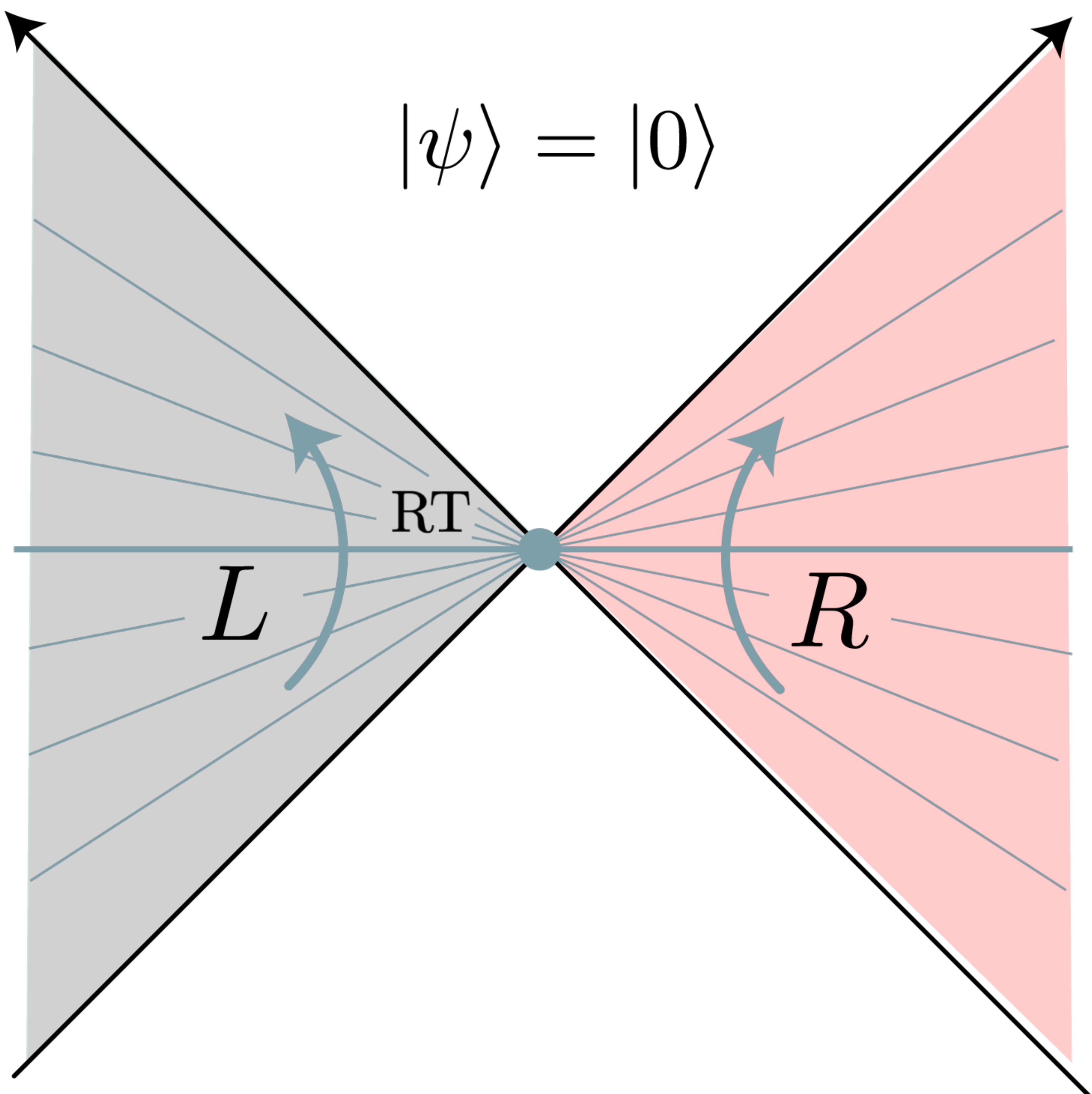
$$\mathrm{Tr}_{sys}\left[\rho_{sys}\left[\rho_{sys}^{-is}\phi_R\rho_{sys}^{is}, O_L\right]\right]$$





WHAT ABOUT OUT-OF -LOCAL EQUILIBRIUM STATES?

Toy example: How are Lorentz boosts defined?



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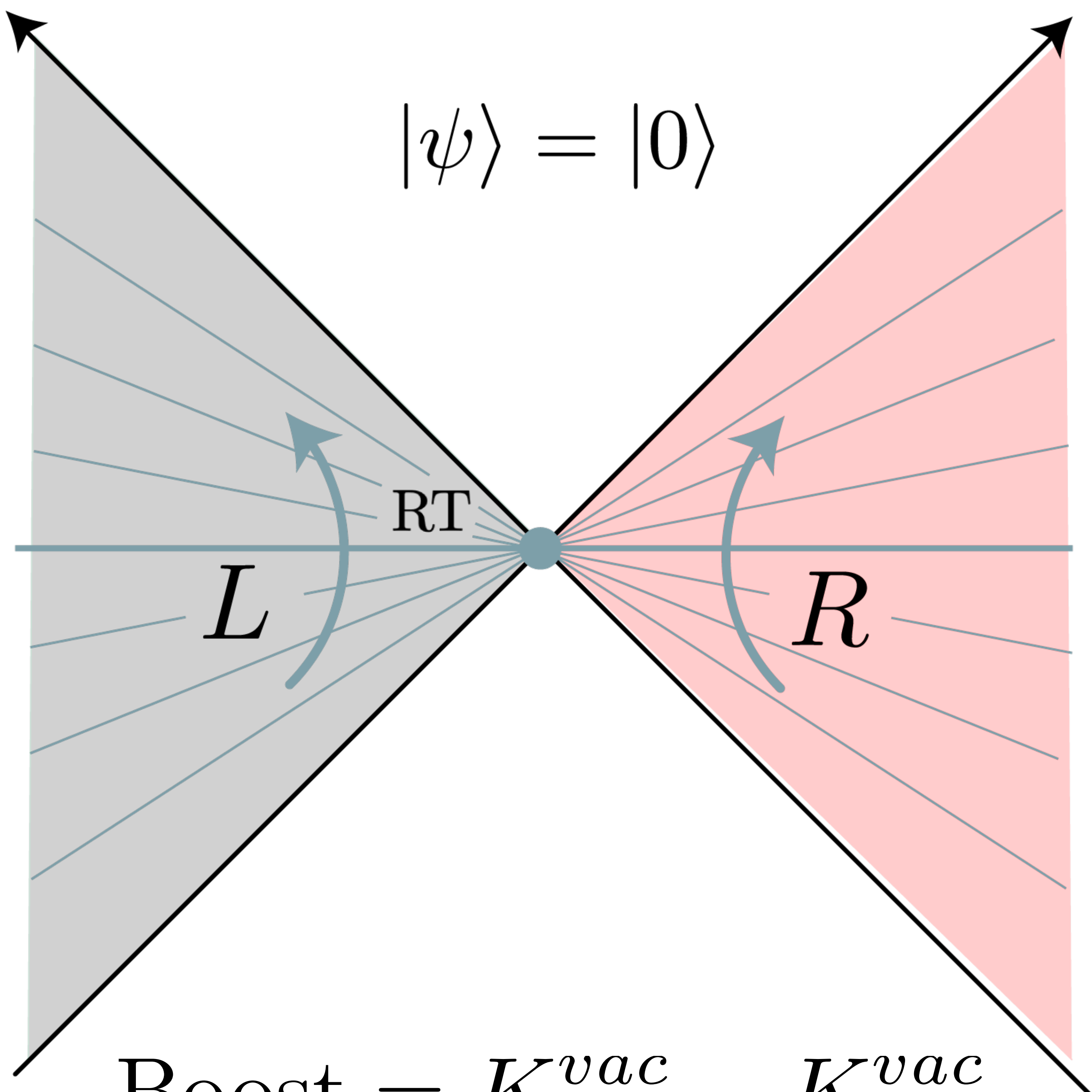

$$\text{Boost} = K_L^{vac} - K_R^{vac}$$

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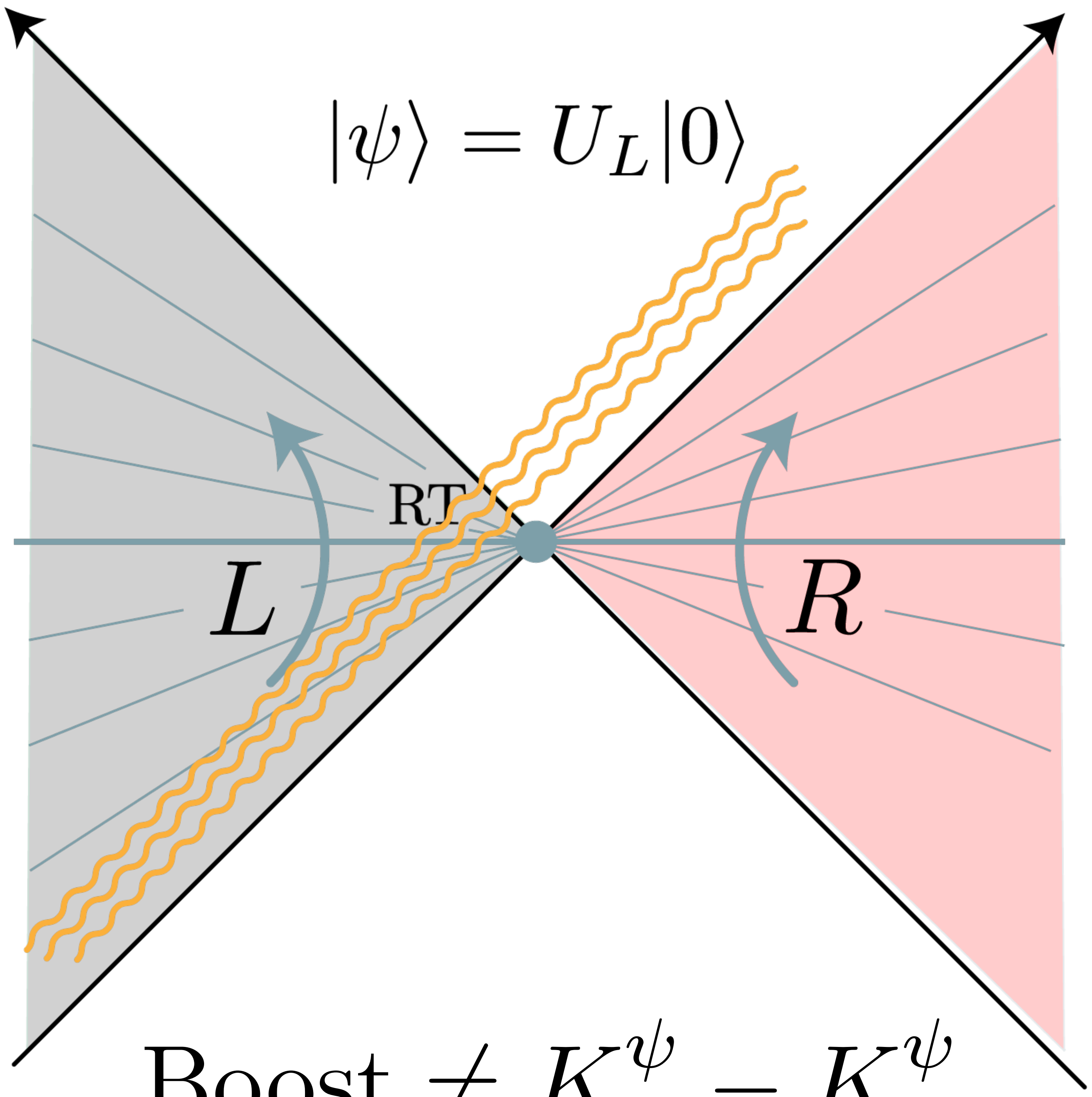
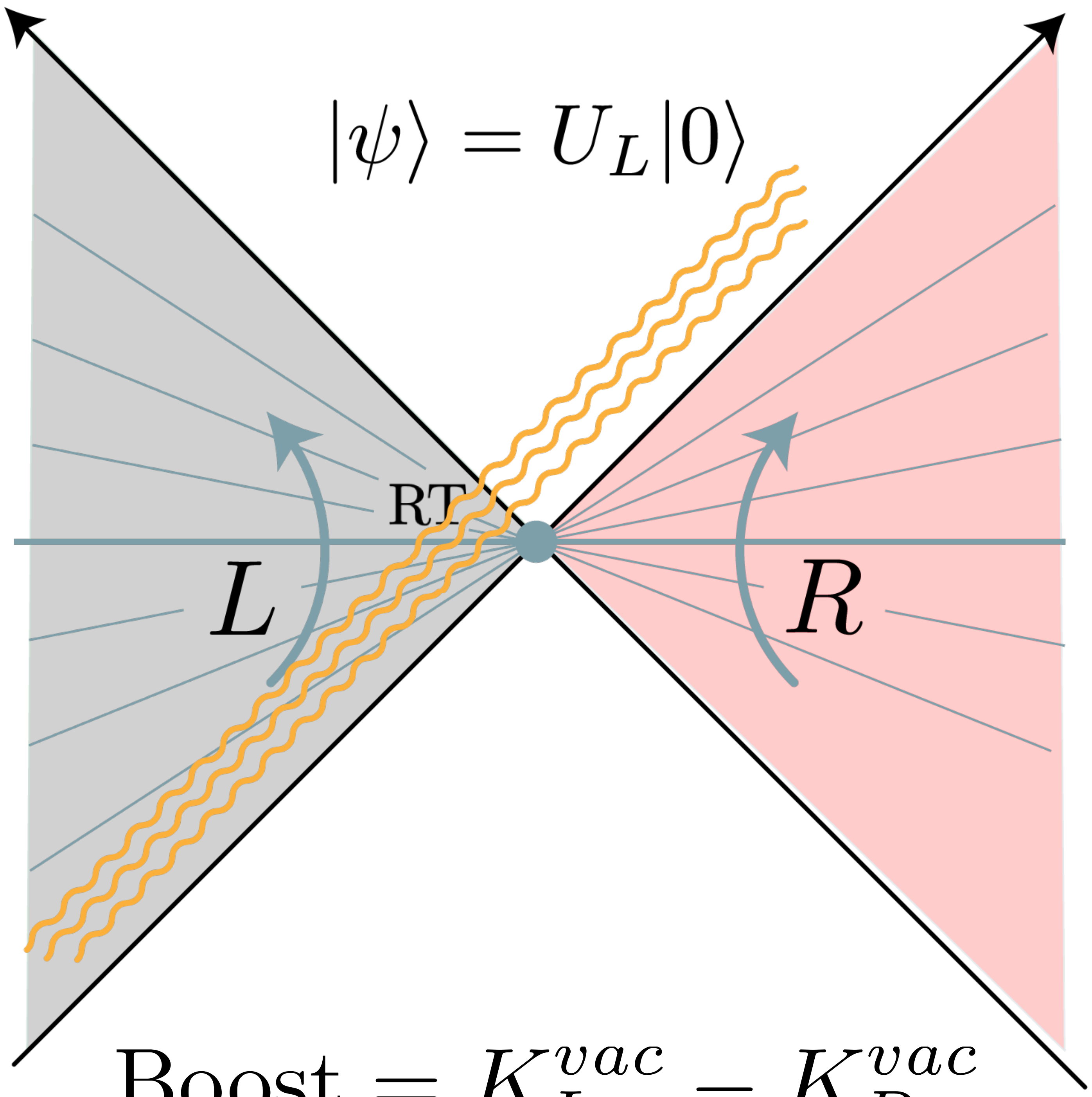


$$\text{Boost} \neq K_L^{\psi} - K_R^{\psi}$$

Toy example: How are Lorentz boosts defined?



$$\text{Boost} = K_L^{vac} - K_R^{vac}$$

Lorentz boosts are generated by the modular Hamiltonian K

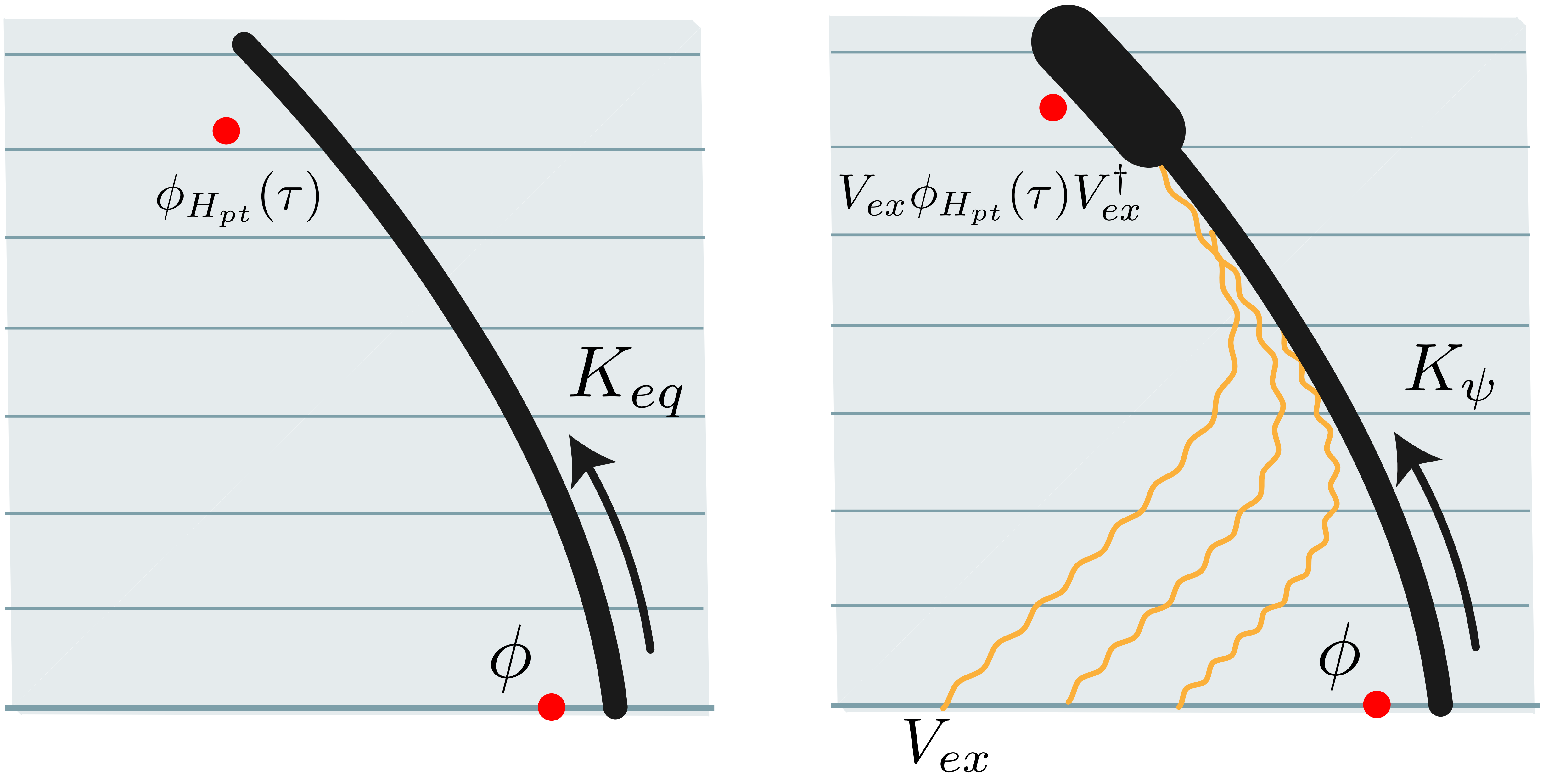
of the state $|0\rangle = U|\psi\rangle$ that minimizes $\langle H_{global}\rangle$

QFT vacuum $\longrightarrow$ Local equilibrium state

Lorentz boost $\longrightarrow$ Local Schwarzschild translation

Minimization of $\langle H \rangle$ $\longrightarrow$?

Equilibrium vs non-equilibrium: Scrambling



$|\psi\rangle$ describes an observer in local equilibrium iff:

$$\max_{O} |\langle \phi_{K_\psi}(\tau \to t_{scr}) O \rangle_\psi| = O(1)$$

In that case: $K \to H_{pt}$ in the atmosphere

The local proper time generator $H_{p.t}$

is the modular Hamiltonian K_U for the state $U|\psi\rangle$

which maximizes $|\langle \phi_{K_U}(\tau \to t_{scr}) O \rangle_\psi|$

among all $U : \mathcal{H}^\psi_{code} \to \mathcal{H}^\psi_{code}$

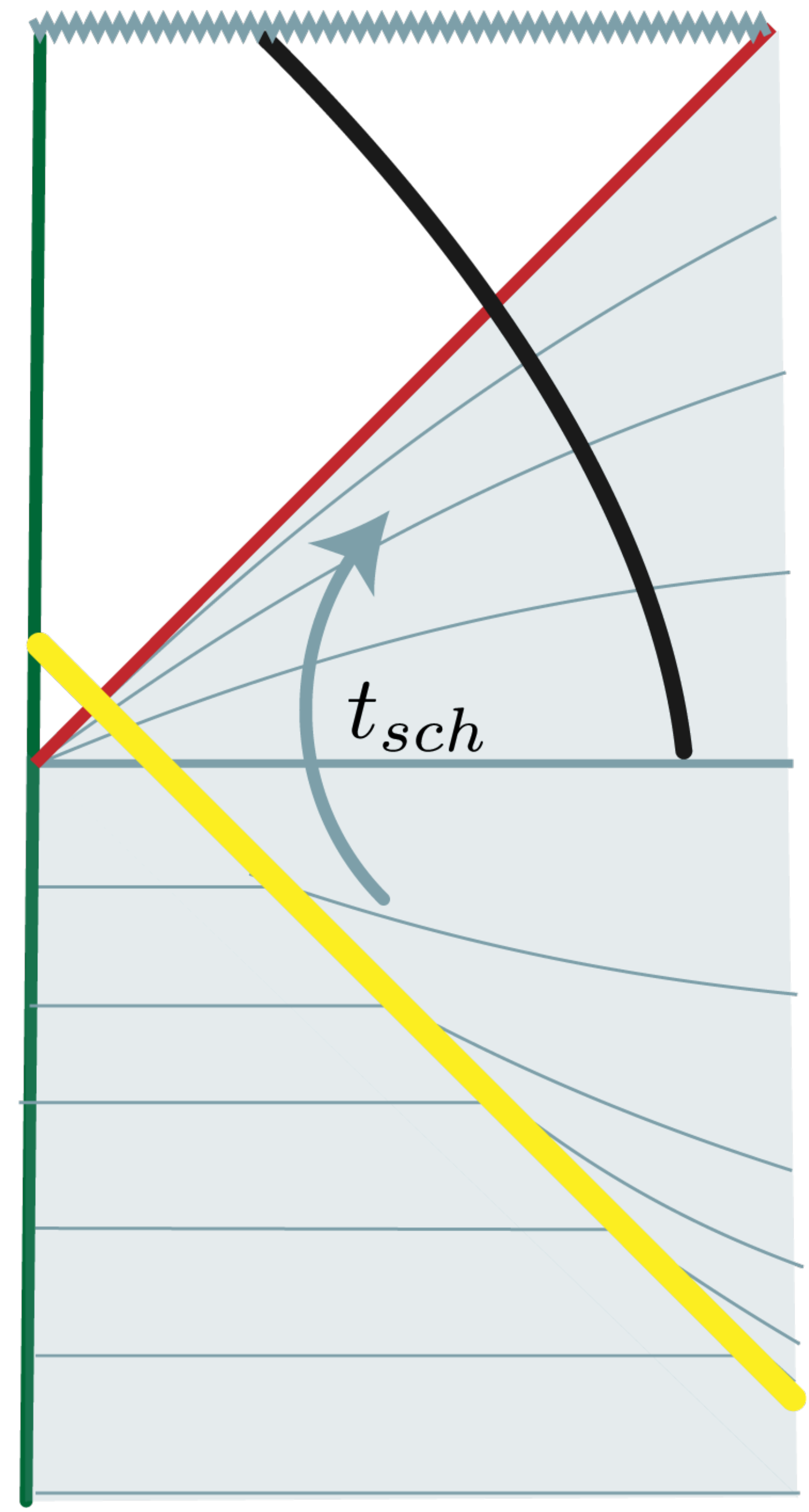
The fine print

We need: $t_{scr}^{probe} \ll L_{AdS}$

Only possible for *microcanonical* black hole probes

$$|\text{microTFD}\rangle = \mathcal{Z}^{-1/2} \sum_E f(E) e^{-\beta E/2} |E\rangle_{sys} |E\rangle_{ref}$$

$$\frac{t_{scr}^{probe}}{L_{AdS}} \propto \left(\frac{L_{AdS}}{\ell_{pl}} \right)^{\frac{1-d}{2d-1}} \log \frac{L_{AdS}}{\ell_{pl}} \ll 1$$



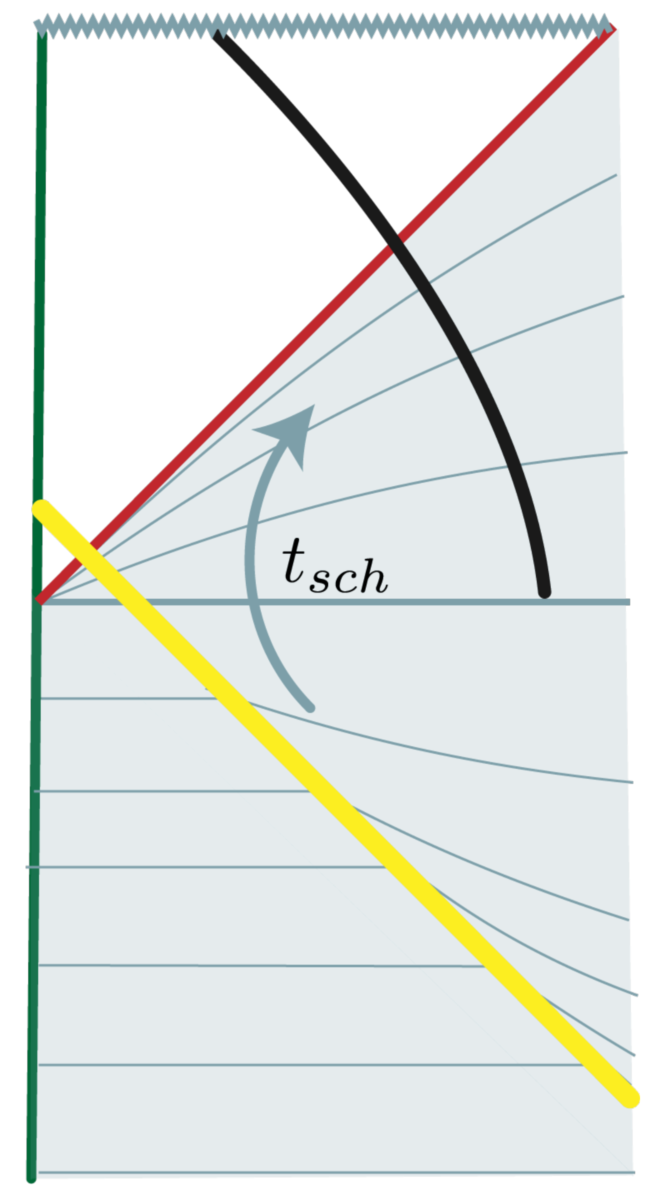
Question 3: Are typical black hole interiors smooth?

Answer 3: I do not know

BUT question can be rephrased:

Is probe modular Hamiltonian
in *local equilibrium*?

$$\max_{O} \left|\langle \phi_{K_\psi}(x,\tau) O(y,t)\rangle_\psi\right| = O(1)$$



A framework for emergent time